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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF A RAM JET BURNING MAGNESIUM SLURRY FUEL AND HAVING A CONICAL SHOCK INLET DESIGNED FOR A MACH NUMBER OF 4.1

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FLIGHT INVESTIGATION OF A RAM JET BURNING MAGNESIUM SLURRY FUEL AND HAVING A CONICAL SHOCK INLET DESIGNED FOR A MACH NUMBER OF 4.1

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SUMMARY

A flight investigation was made of a rocket-launched ram-jet engine incorporating an inlet designed for a Mach number of 4.1 and burning magnesium slurry fuel. In free flight, the model accelerated from a Mach number of 1.73 and an altitude of 5,900 feet until burnout at a Mach number of 3.84 and an altitude of 38,100 feet in an elapsed time of 13.2 seconds. Maximum values of acceleration (6.1g), air specific impulse (150 seconds), and gross thrust coefficient (0.760) were obtained. The value of fuel specific impulse was 770 seconds.

INTRODUCTION

The NACA is conducting a program to develop new high-energy fuels for use in turbojet and ram-jet engines. One such fuel is a metal slurry fuel made up of finely divided metal particles suspended in liquid hydrocarbons. Preliminary results obtained in a connected pipe facility at the Lewis high energy fuels laboratory (ref. 1) indicated the feasibility of adapting this fuel to a flight test vehicle similar to that previously tested at the Langley Pilotless Aircraft Research Station at Wallops Island, Va. Such a test was conducted and the results are reported in reference 2.

The data of reference 2 indicated that the fuel performed satisfactorily. The test vehicle accelerated from a Mach number of 1.75 to Mach number of 3.48 with a maximum acceleration of 4.6g. However, since the test vehicle employed a conical shock inlet designed for a Mach number of 2.13, it was felt that the performance could be improved by employing a more suitable inlet configuration. Accordingly, a second test vehicle was designed identical to that of reference 2, except that it incorporated a conical shock inlet designed for a Mach number of 4.10.

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The results of the flight test of this vehicle, as well as some performance parameters obtained in the preflight jet prior to the flight test, are presented in this paper. All tests were made at the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

SYMBOLS

t	time measured from take-off, sec
p	static pressure, lb/sq in. abs
T	static temperature, $^{\circ}R$
A_{∞}	maximum free-stream tube area, sq ft
M	free-stream Mach number
S_a	sonic air specific impulse, $\frac{\text{Jet thrust, lb}}{\text{Air, lb/sec}}$
C_{T_g}	gross thrust coefficient, based on combustion-chamber area
C_{T_n}	net thrust coefficient, based on combustion-chamber area
C_D	external drag coefficient, based on combustion-chamber area
T_S	stagnation temperature, $^{\circ}R$
ϕ M	ratio of jet impulse at exit to jet impulse at sonic station

APPARATUS AND METHODS

Model

The model incorporating a conical shock inlet diffuser designed for a Mach number of 4.1 is shown as a sketch and as a photograph in figures 1(a) and 1(b), respectively. The combustion-chamber area was 2.87 times the annular area at the inlet lip. The inner body assembly consisted of the entrance cone, the fuel tank, and the burner apparatus. The model was 75.43 inches in length with a $6\frac{1}{2}$-inch-diameter combustion chamber, upon which four fins, each with an exposed area of 0.416 square foot, were mounted. An exit nozzle, contracted and then

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expanded to 0.852 and 0.925, respectively, of the combustion-chamber area, was attached at the aft end of the combustor.

The combustor was constructed of 3/32-inch Inconel sheet. The exit nozzle and stabilizing fins were stainless steel. The remainder of the model was of mild steel. The empty model weight was 73.1 pounds.

Fuel and Fuel System

The high-energy fuel used in this investigation consisted of magnesium powder suspended in a liquid hydrocarbon (JP-4). The slurry fuel was developed at the Lewis Flight Propulsion Laboratory and comprehensive information on its performance as obtained in ground tests is reported in references 1, 3, and 4. The pertinent information on the fuel used in this investigation is as follows:

Specific gravity	1.07
Particle size (maximum diameter), microns	1

The fuel consisted of 52.4 percent by weight of magnesium powder, 47.1 percent by weight of JP-4 liquid hydrocarbon, and 0.5 percent by weight of a wetting agent. The assay of the metal powder was 93.6 percent pure magnesium and 0.9 percent pure aluminum, with 5.5 percent magnesium oxide. The weight of fuel carried in the flight model was 14.69 pounds.

The rocket gas generator (fig. 1(c)) which was used in the fuel pumping system was designed by the methods of reference 2. A Cordite SU/K propellant grain having a weight of 80 grams, with a diameter and length of $1\frac{1}{16}$ and $3\frac{1}{2}$ inches, respectively, was fired with two 5-delay electric squibs and generated the gases used to expel the fuel from the fuel tank. The generator, which was attached to the head cap of the fuel tank, was made of SAE 4130 steel and had a loaded weight of $1\frac{1}{2}$ pounds. The rocket gases and fuel were separated by a free-floating piston (fig. 1(d)). A 0.104-inch-diameter flowmetering nozzle, located immediately in front of the injector-burner assembly, was used to meter the fuel flow to the engine. A complete description of the injector and flame holder design (fig. 1(e)) is given in reference 1. For the investigation reported herein, however, the length of the burner was cut down from $7\frac{1}{2}$ inches to 4 inches, as was done in reference 2.

A magnesium flare was cemented into the flame holder and fired at take-off to serve as an igniter for the fuel. An aluminum annular igniter-ring starting disk, blocking 47 percent of the combustor area, was inserted immediately in front of the exit nozzle. The starting-disk technique is described in reference 5.

The performance of the inlet diffuser, fuel system, burner, and fuel were obtained prior to the flight test in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

Booster Rocket and Adapter

A JATO, 3.5-DS-5700 rocket motor was used to accelerate the ram jet to supersonic speed. A cast magnesium-alloy coupling fastened to the rocket motor and fitted internally in the ram-jet exit nozzle attached the ram jet to the booster. This coupling was designed to block only 10 percent of the nozzle exit area during the boost period. Four fins, each with an area of $1\frac{1}{4}$ square feet, were mounted at the rear end of the booster rocket motor and provided stability of the combination during the boost period. A photograph of the ram jet and coupled booster in place on the launcher prior to firing is shown as figure 2.

Measurements

The velocity of the model in flight was measured with CW Doppler radar. The position of the model in space was determined with NACA modified SCR-584 tracking radar. High-speed manually operated tracking cameras provided information on the behavior of the model during the initial portion of the flight.

Upon completion of the flight test, a radiosonde balloon was released to obtain the pressure, temperature, and altitude relationship. The wind-velocity-altitude relationship was obtained by tracking the balloon with a rawinsonde. The variation of static pressure p and static temperature T, obtained from the radiosonde data, with altitude is presented in figure 3.

RESULTS AND DISCUSSION

Free Jet Test

Prior to the flight test, the performance of the flight configuration from the flameholder forward was checked in a free jet at $M = 2.03$. The finned combustor and expanding exit nozzle were replaced with a finless combustor of the same length having a 6-inch-diameter sonic exit for the preflight test. A photograph of the model mounted in the $M = 2.03$ free jet is shown as figure 4. The test was conducted with $T_s = 825^\circ \pm 6^\circ$ R and $p = 13.2 \pm 0.2$ lb/sq in. abs. The results of this test are presented as a time history of S_a (obtained by the method of ref. 5) in figure 5. The weight flow of air was determined by using the relationship of maximum stream tube area to Mach number obtained from reference 6, as shown in figure 6. The engine "buzzed" for approximately 0.7 second while the starting disk burned out before the value of S_a markedly increased. (See fig. 5.) Maximum values of S_a of 126 seconds were obtained during the test. In this test the length of gas generator grain was $3\frac{1}{4}$ inches, $\frac{1}{4}$ inch less than the length used on the flight model, and the fuel weight was 13.50 pounds. The fuel was completely expelled from the tank 12.1 seconds after ignition.

Flight Test

The altitude and horizontal range coordinates, as obtained from the data of the SCR-584 radar, are presented in figure 7 up to the point where radar contact was lost. The altitude-time data are also presented for the powered portion of the flight. The pertinent events and the times at which they occurred in flight are noted on the figure.

The flight Mach number M of the ram jet is presented in figure 8 as a function of flight time. Velocity data determined by the CW Doppler velocimeter were used in these calculations after appropriate corrections for wind velocities at the various altitudes were made. The model separated from the booster at $M = 2.00$ and decelerated through the ignition stage at $M = 1.82$ until the starting disk burned out at $M = 1.73$. The data then show a peak value of $M = 3.84$ was obtained at the time of 18.1 seconds. During this period, maximum values of longitudinal acceleration of 6.1g were calculated from the data. The Reynolds number, based on body length, varied between 72×10^6 and 49×10^6 during the powered portion of the flight. It is interesting to note that when radar contact was lost at 113,400 feet altitude (see fig. 7), a Mach number slightly in excess of 1.8 was computed from the data.

The gross thrust coefficient C_{T_g} of the ram-jet engine is presented in figure 9 as a function of Mach number. The net thrust was calculated from the longitudinal acceleration data (obtained from CW Doppler radar set) and the mass of the ram jet (with appropriate corrections for changing mass with fuel consumption). The gross thrust coefficient was obtained from the net thrust coefficient and the computed external drag coefficient C_D also presented in figure 9. The fuel rate was considered constant over the period of ram-jet operation. The external-drag coefficient C_D was estimated from theoretical friction drag (ref. 7) and pressure drag on the engine (ref. 8), two-dimensional pressure drag on the fins, and theoretical values of additive drag of the inlet as obtained from the data of reference 6. A maximum value of $C_{T_g} = 0.76$ was calculated at $M = 2.01$ for these data.

A time history of the air specific impulse S_a delivered by the ram jet is presented in figure 10. The values of S_a, at the sonic section of the exit nozzle, were obtained by adding the gross thrust to the total momentum of the ram-jet entrance air and dividing by the weight flow of air and the thrust function ϕM (ref. 9). The value of ϕM was calculated from the data at the time of 17 seconds with $M = 3.72$. The calculated values of free-stream stagnation temperatures T_S also presented in figure 10 indicate a maximum value of $T_S = 1,560^\circ$ R was reached at $t = 18.1$ which occurs at $M = 3.84$.

The improved performance of the present test vehicle over that reported in reference 2 is illustrated in figure 11 which compares the net thrust coefficients C_{T_n} obtained from the two tests. Below $M = 1.9$, the vehicle employing the $M = 2.13$ design inlet (ref. 2) had a slightly better net thrust coefficient. Above this Mach number, however, the present test vehicle had the higher C_{T_n}, with the difference becoming increasingly greater as Mach number increased up to $M = 3.4$, the limit of the test data of reference 2. At this Mach number, the net thrust coefficient of the present test was 73 percent greater than that achieved in reference 2.

The total fuel load of 14.69 pounds was assumed to have been expended between the times of 4.1 and 18.2 seconds to produce a gross impulse of 11,300 pound-seconds. The ratio of these values demonstrates that the overall value of fuel specific impulse of 770 seconds obtained was approximately 40 percent higher than the value of 549 seconds calculated for similar fuel in an engine designed for a lower starting Mach number (ref. 2).

CONCLUDING REMARKS

The important results obtained in a free-flight test of a rocket-launched ram jet utilizing a magnesium slurry fuel are:

1. The ram jet accelerated from a Mach number of 1.73 at an altitude of 5,900 feet to a Mach number of 3.84 at an altitude of 38,100 feet in the elapsed time of 13.2 seconds.

2. The missile experienced a maximum acceleration of 6.1g during free flight.

3. A maximum value of gross thrust coefficient of 0.76 was calculated at a corresponding drag coefficient of 0.29.

4. A maximum value of air specific impulse of 150 seconds was obtained at a Mach number of 3.72 with the free-stream stagnation temperature equal to 1,470° R.

5. The fuel specific impulse of 770 seconds obtained in the present tests using an inlet designed for Mach number of 4.10 was approximately 40 percent greater than that previously reported for a vehicle using an inlet designed for a Mach number of 2.13.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 5, 1956.

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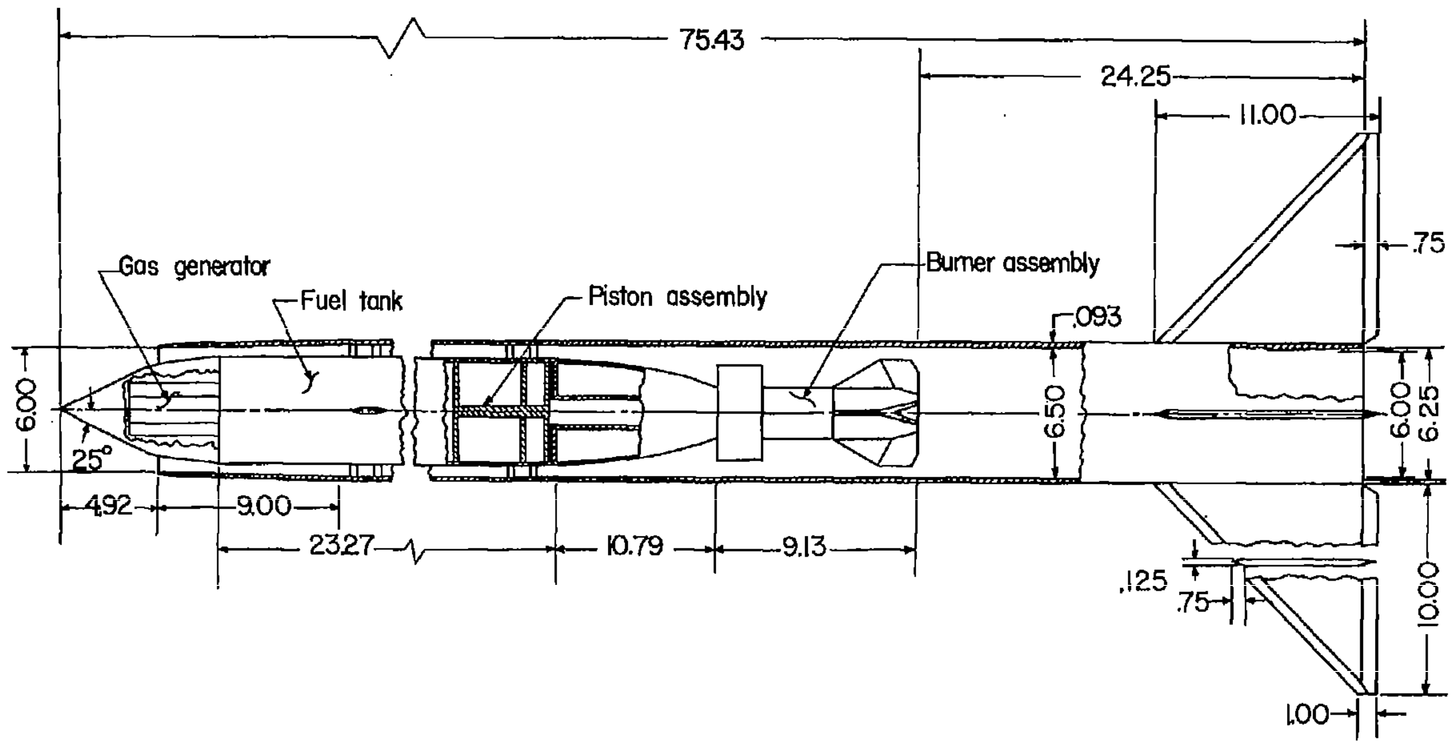
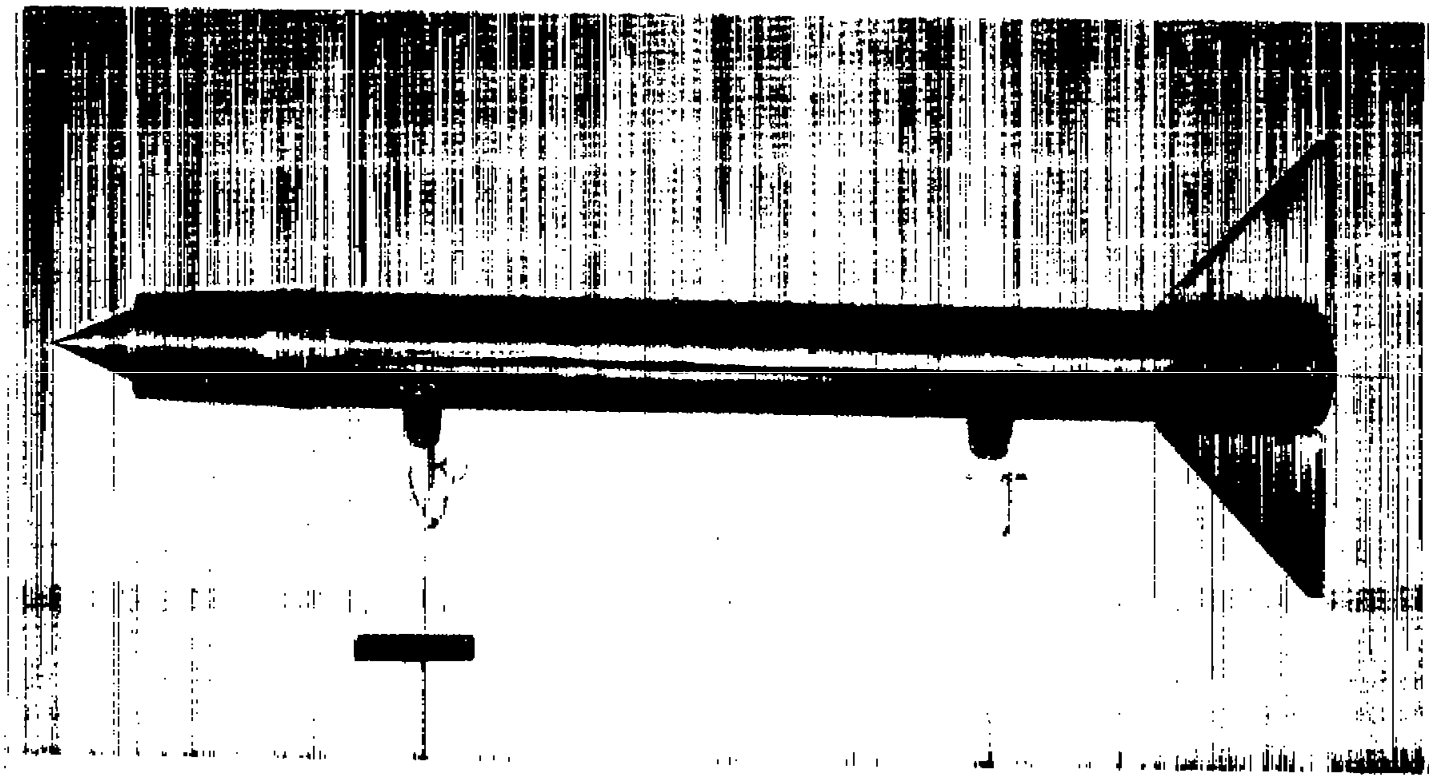


(a) Sketch of model. All dimensions are in inches.

Figure 1.- The slurry-fuel ram jet.



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(b) Photograph of the model.

Figure 1.- Continued.

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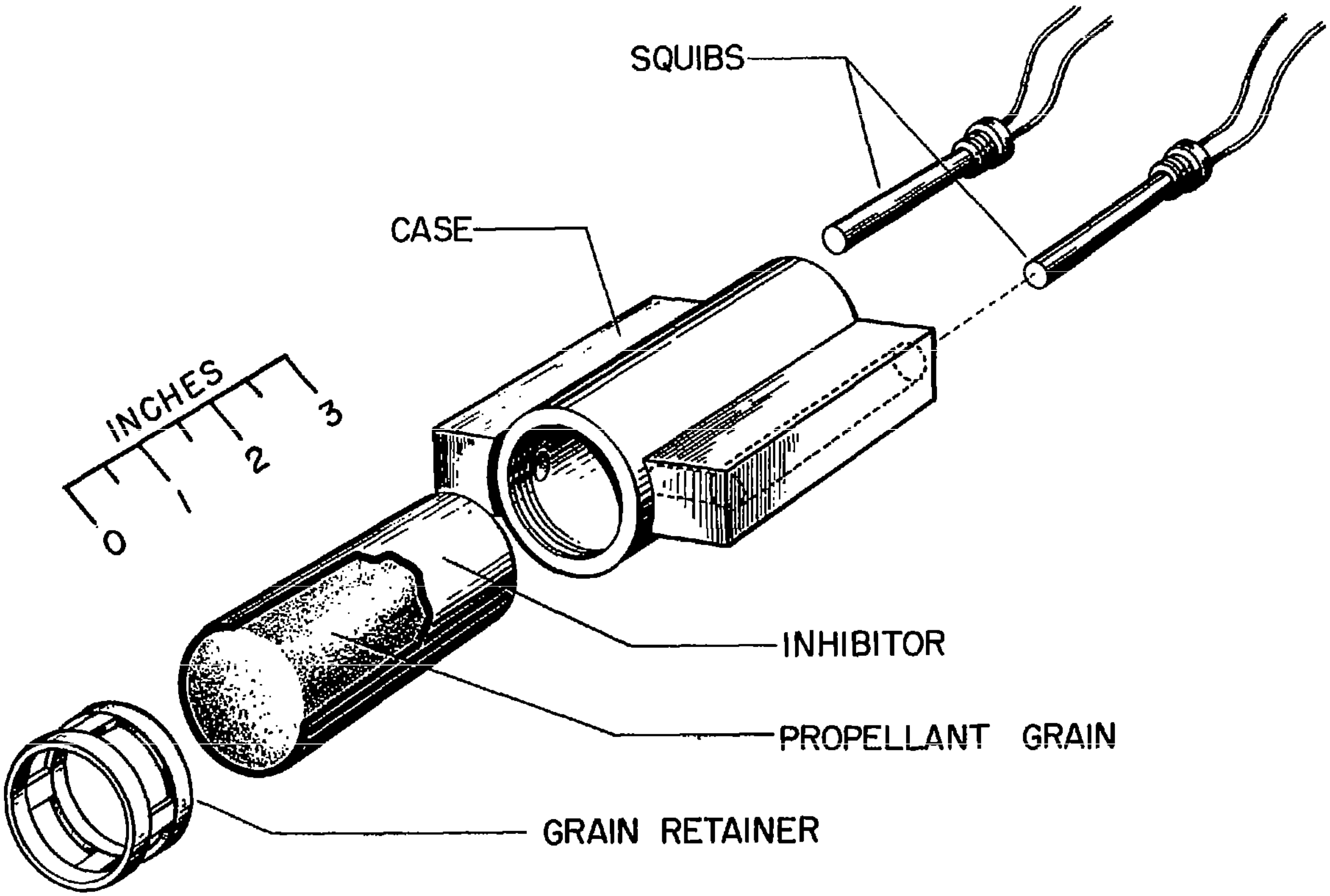

(c) Rocket gas generator.

Figure 1.- Continued.

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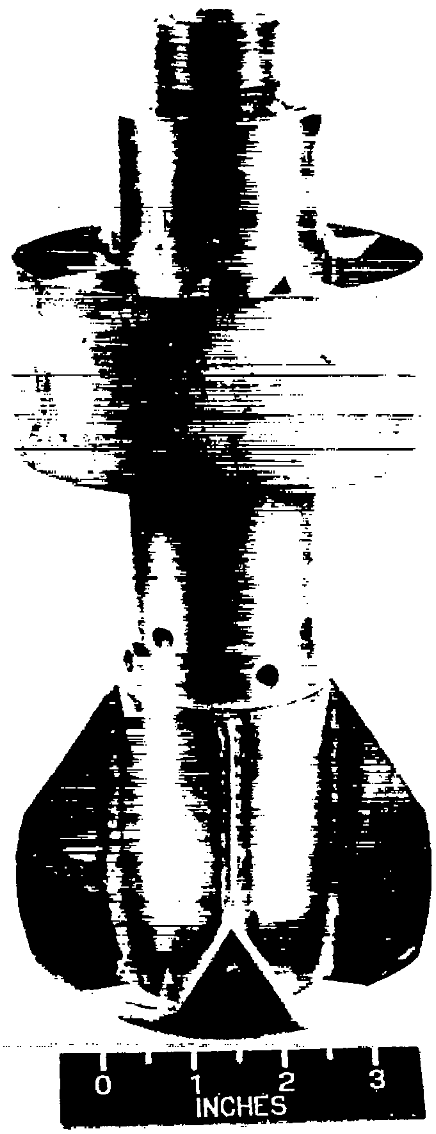
(d) Photograph of piston.

Figure 1.- Continued.



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(e) The fuel injector-burner assembly.

Figure 1.- Concluded.

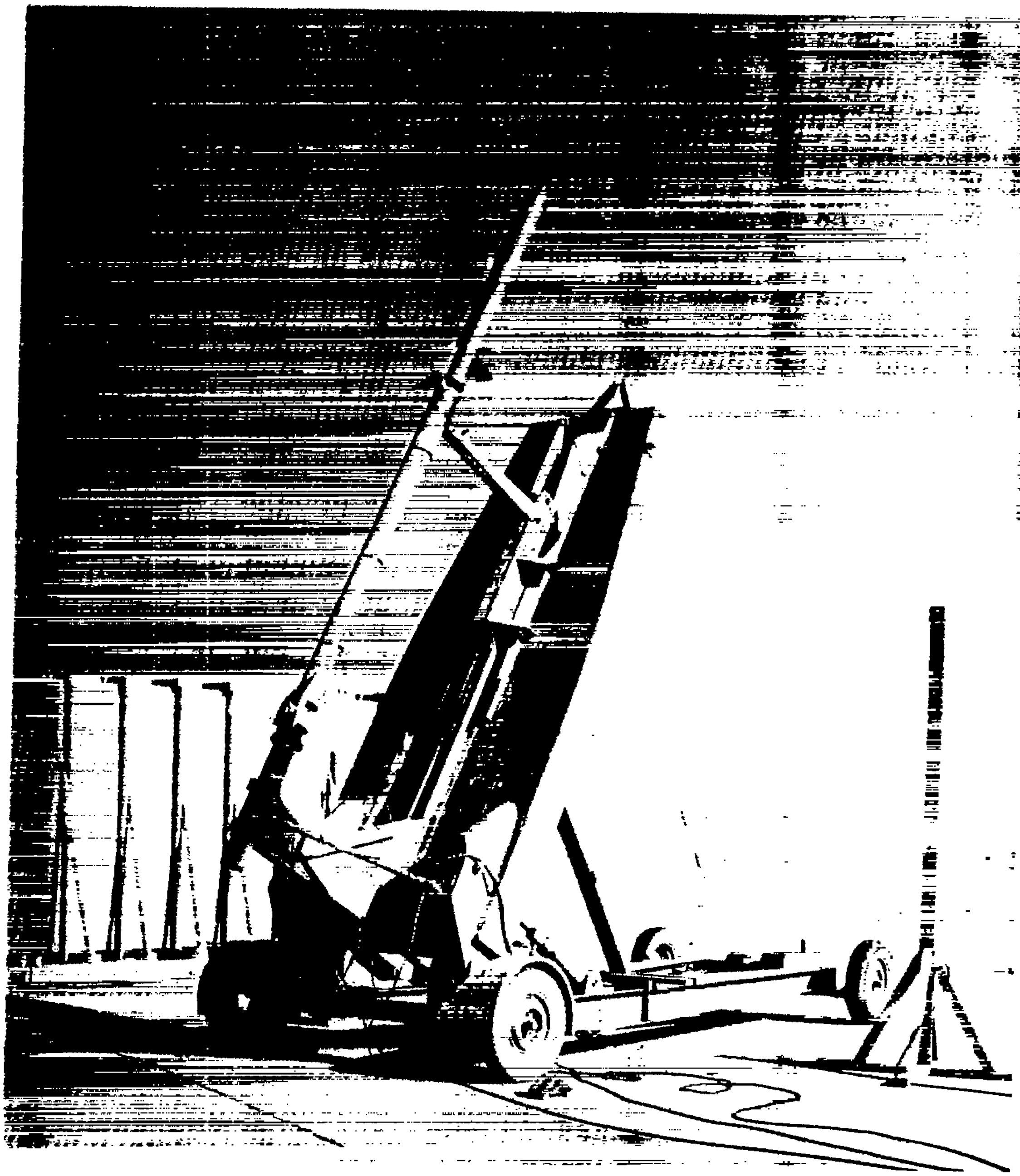

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Figure 2.- The model and booster on the launcher.

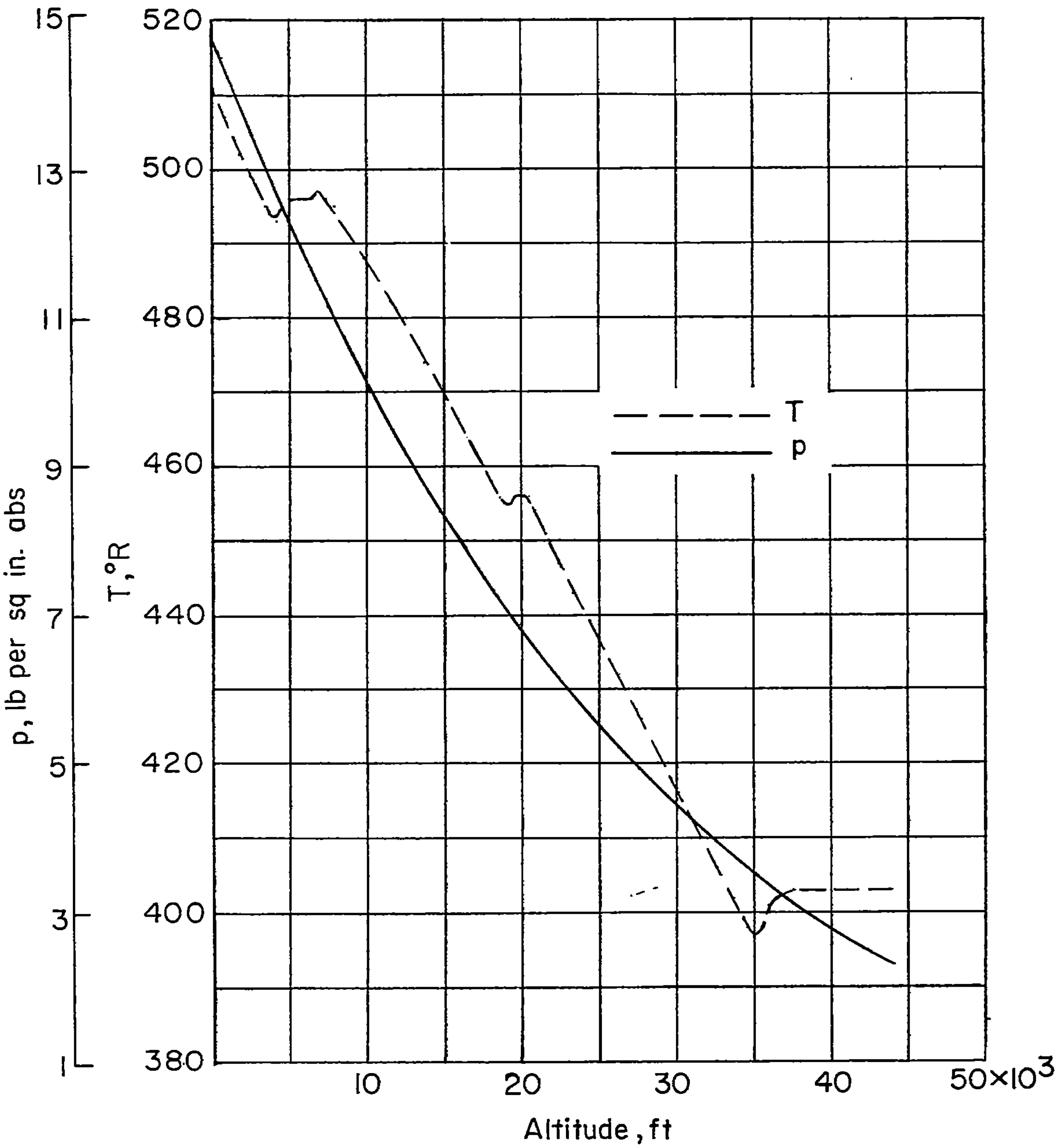

Figure 3.- Variation of ambient pressure and temperature with altitude.

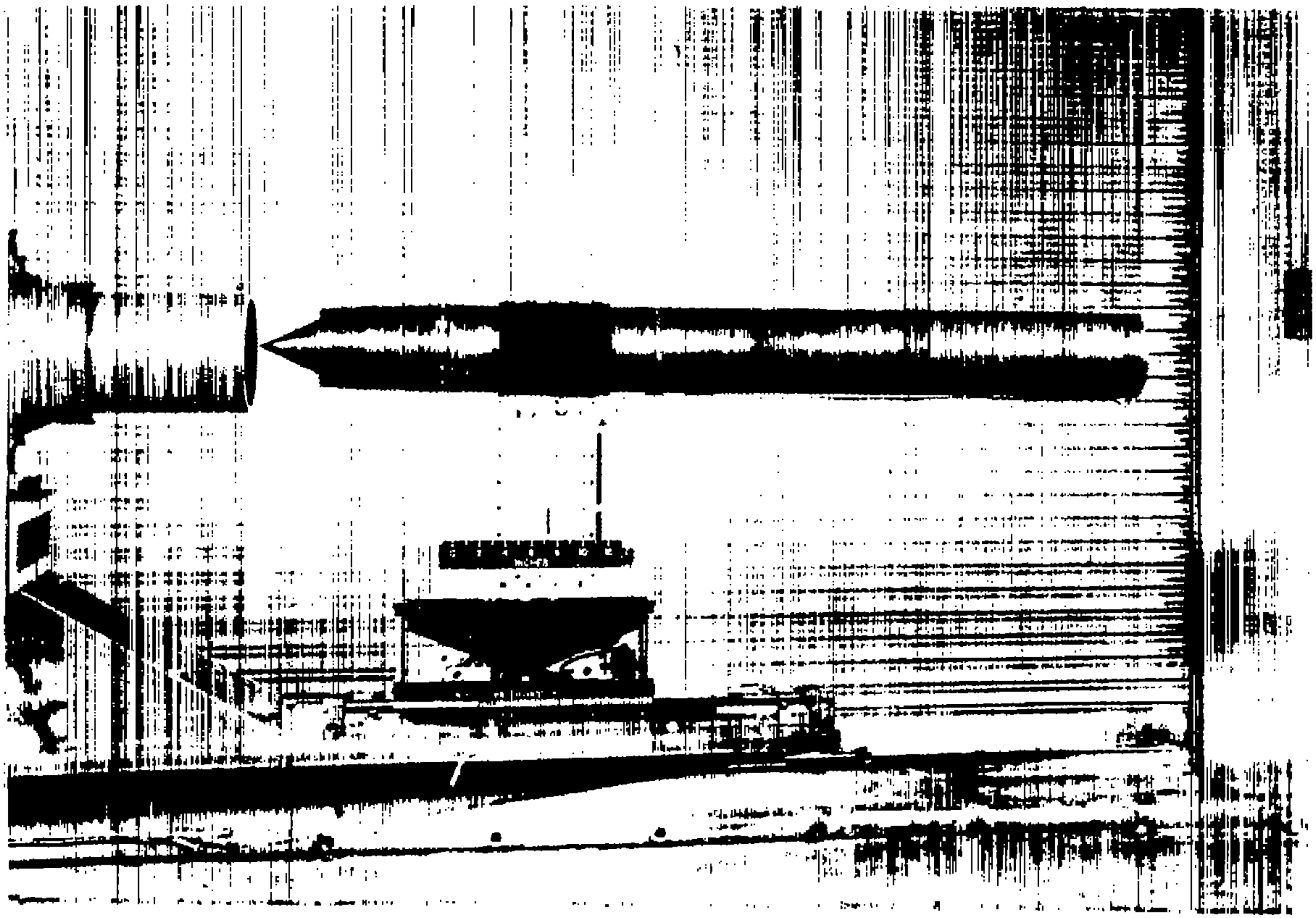

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Figure 4.- Photograph of preflight model mounted in $M = 2.03$ free jet.

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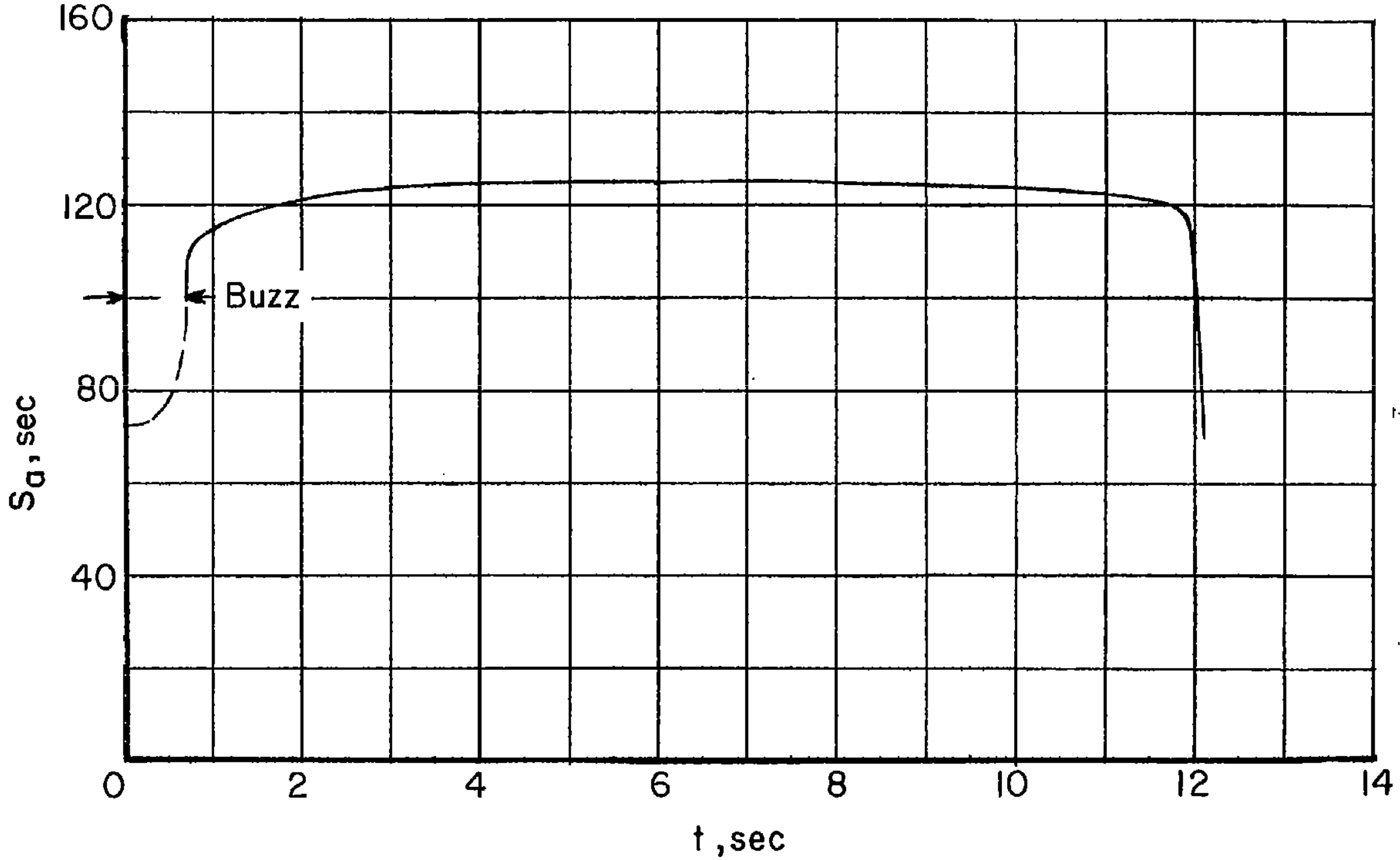

Figure 5.- Time history of air specific impulse obtained from preflight-jet test.

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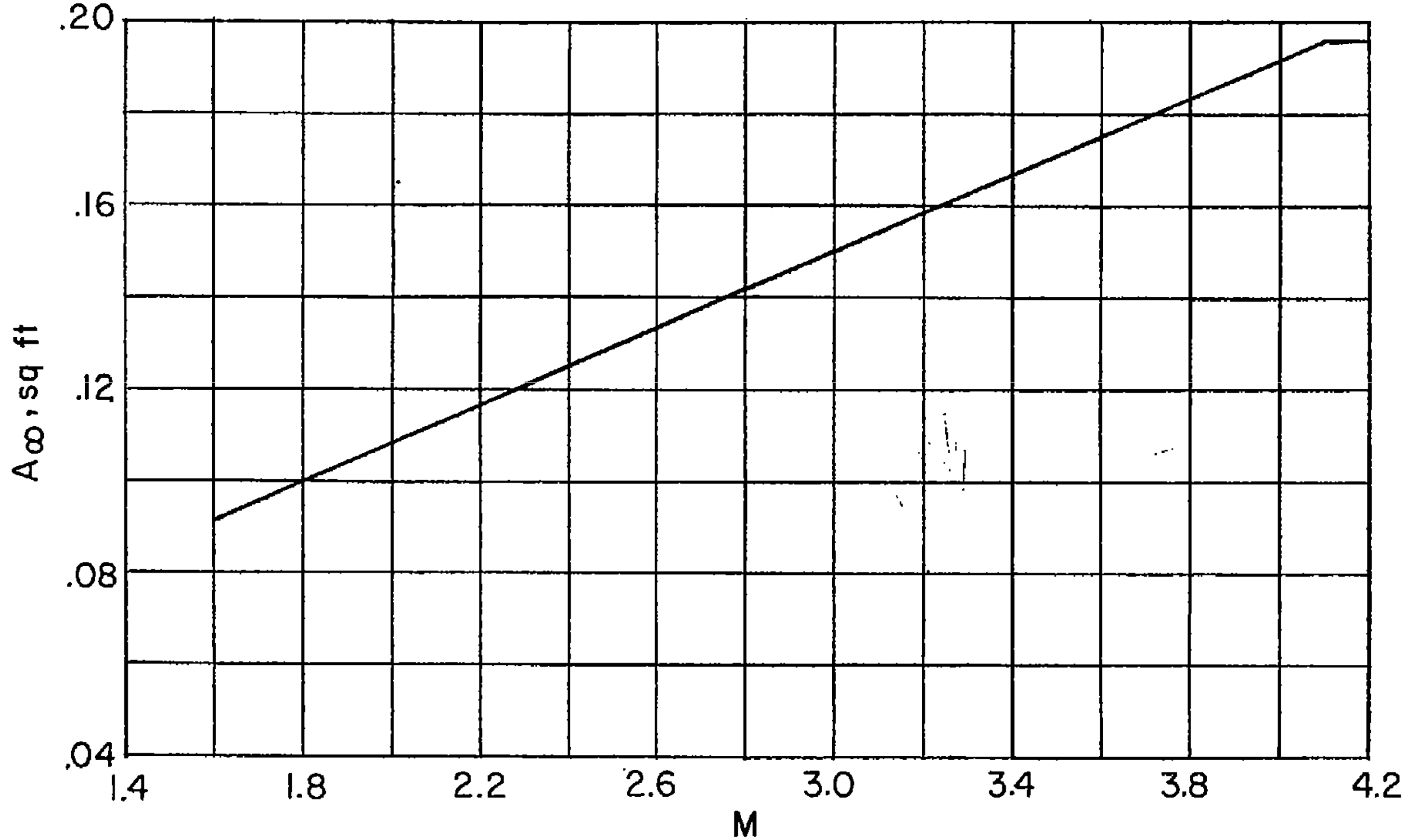

Figure 6.- Variation of maximum free-stream tube area with flight Mach number.

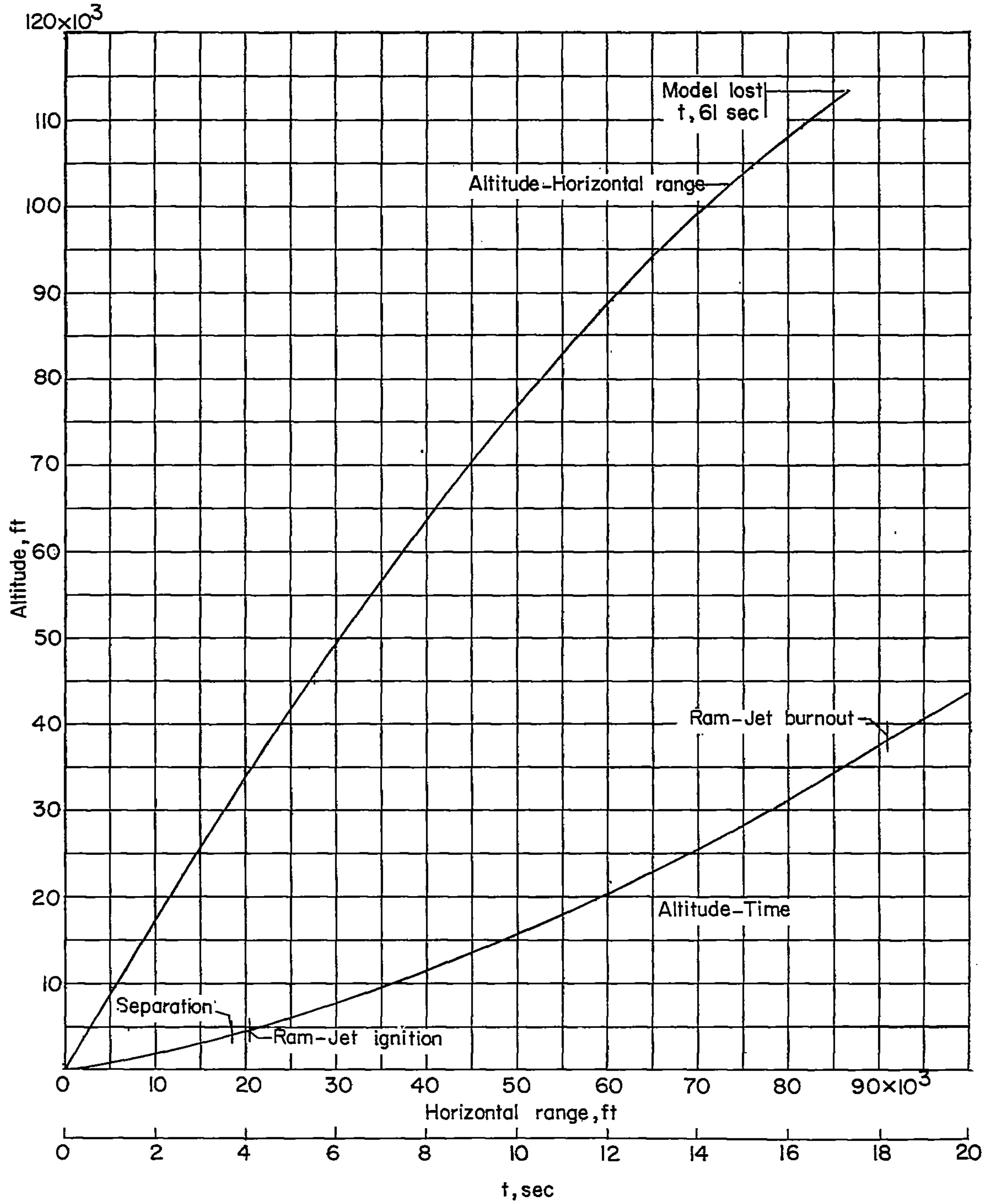

Figure 7.- Variation of altitude with horizontal range and flight time.

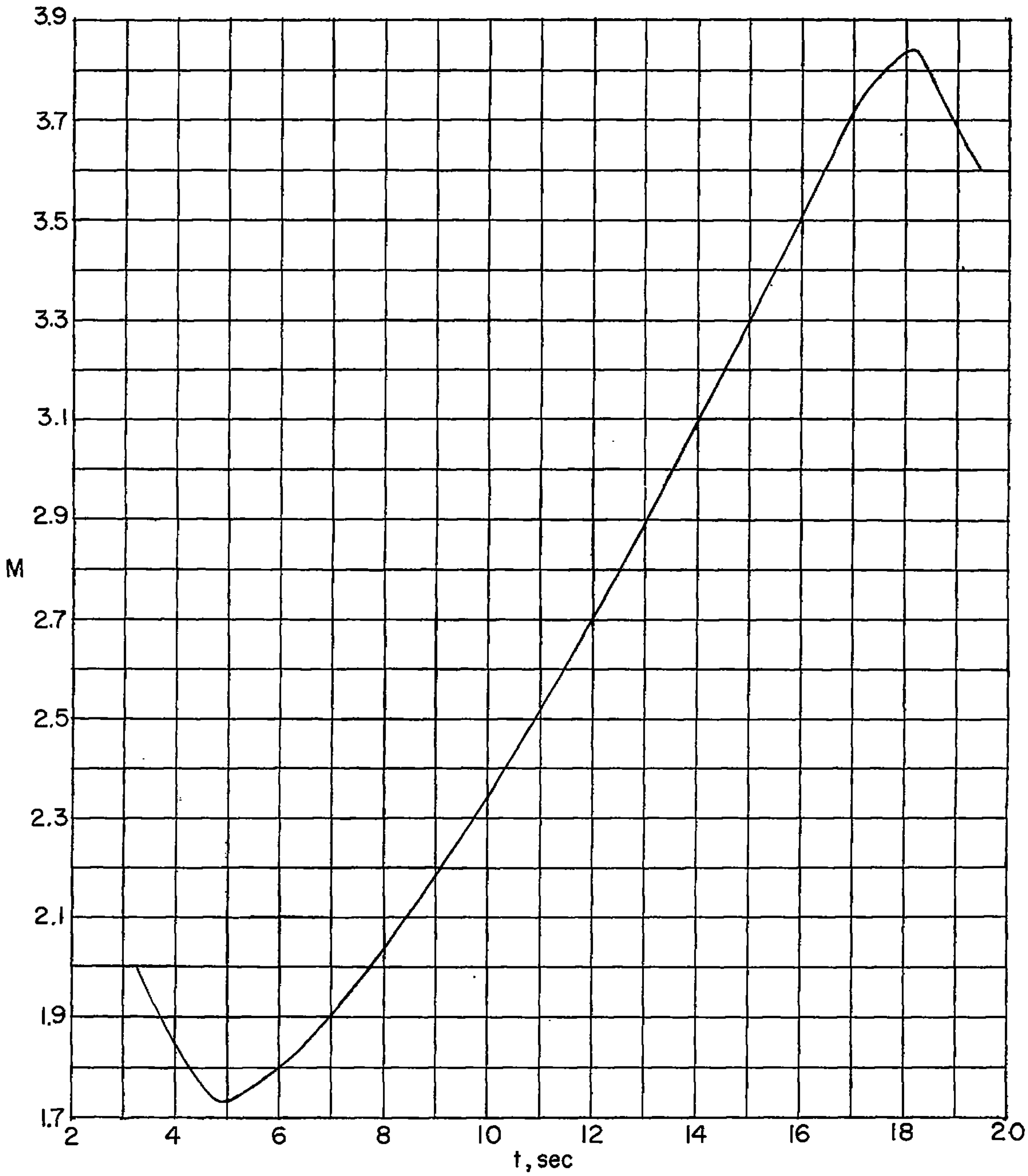

Figure 8.- Flight Mach number against time.

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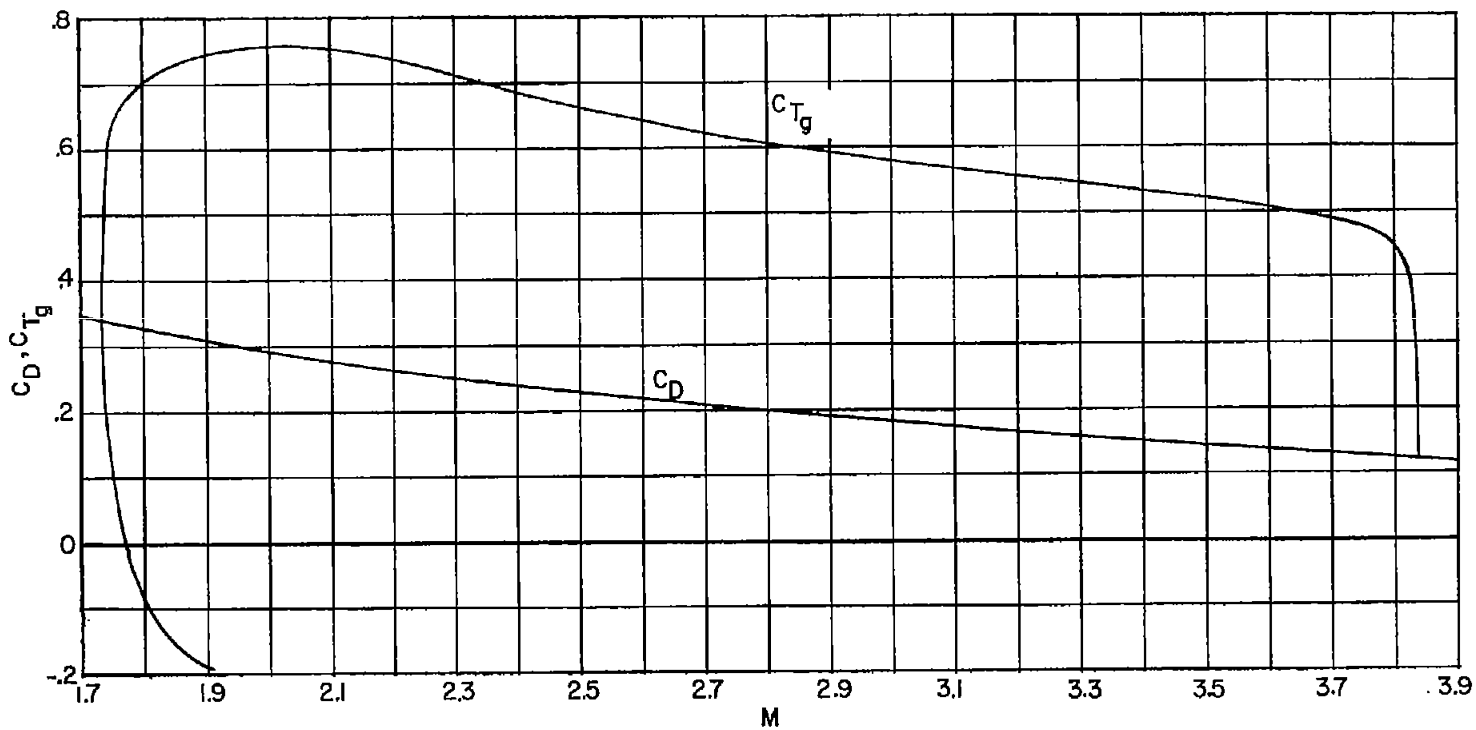

Figure 9.- Variation of gross thrust and external drag coefficients with flight Mach number.

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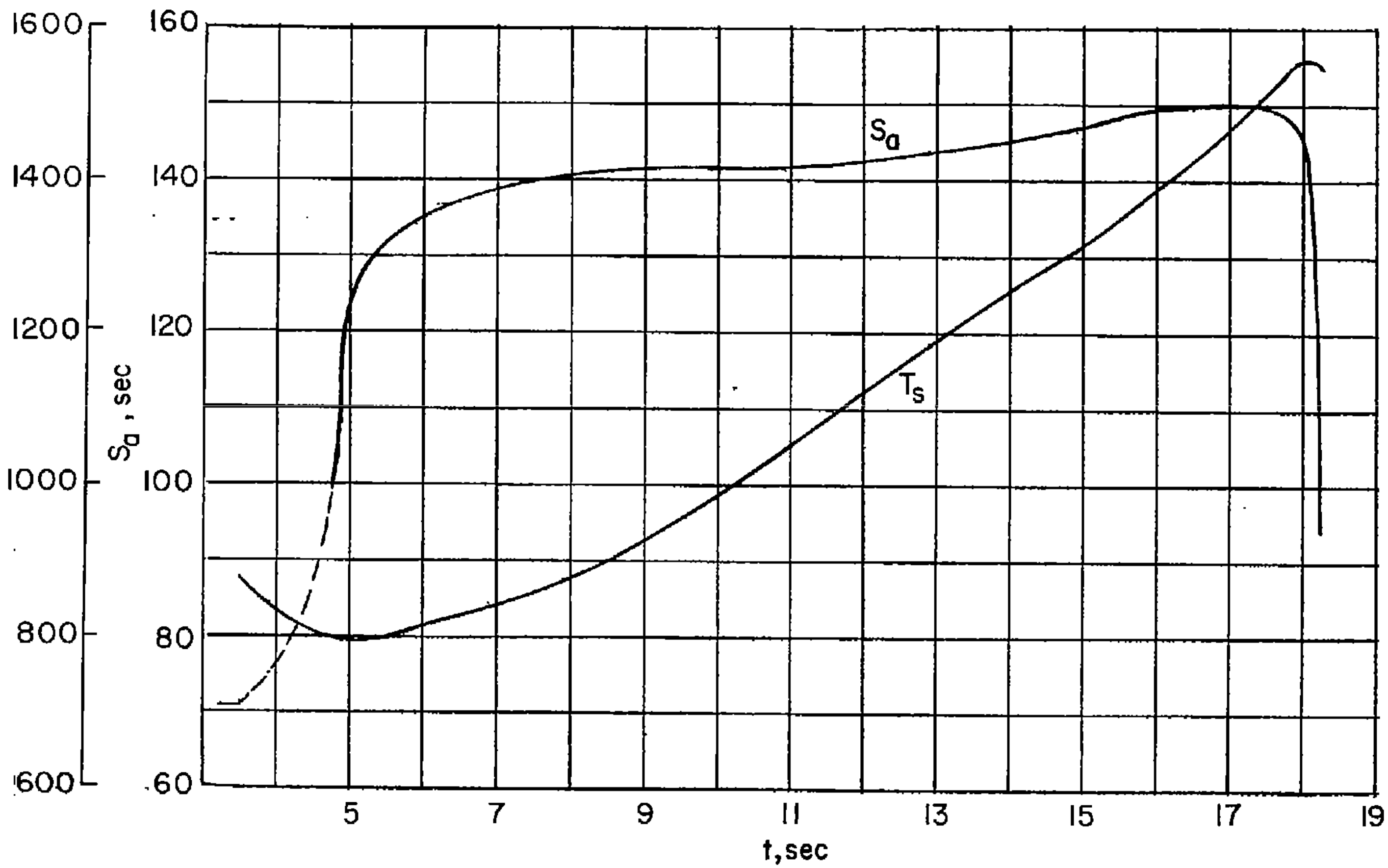

Figure 10.- Air specific impulse and stagnation temperature plotted against time.

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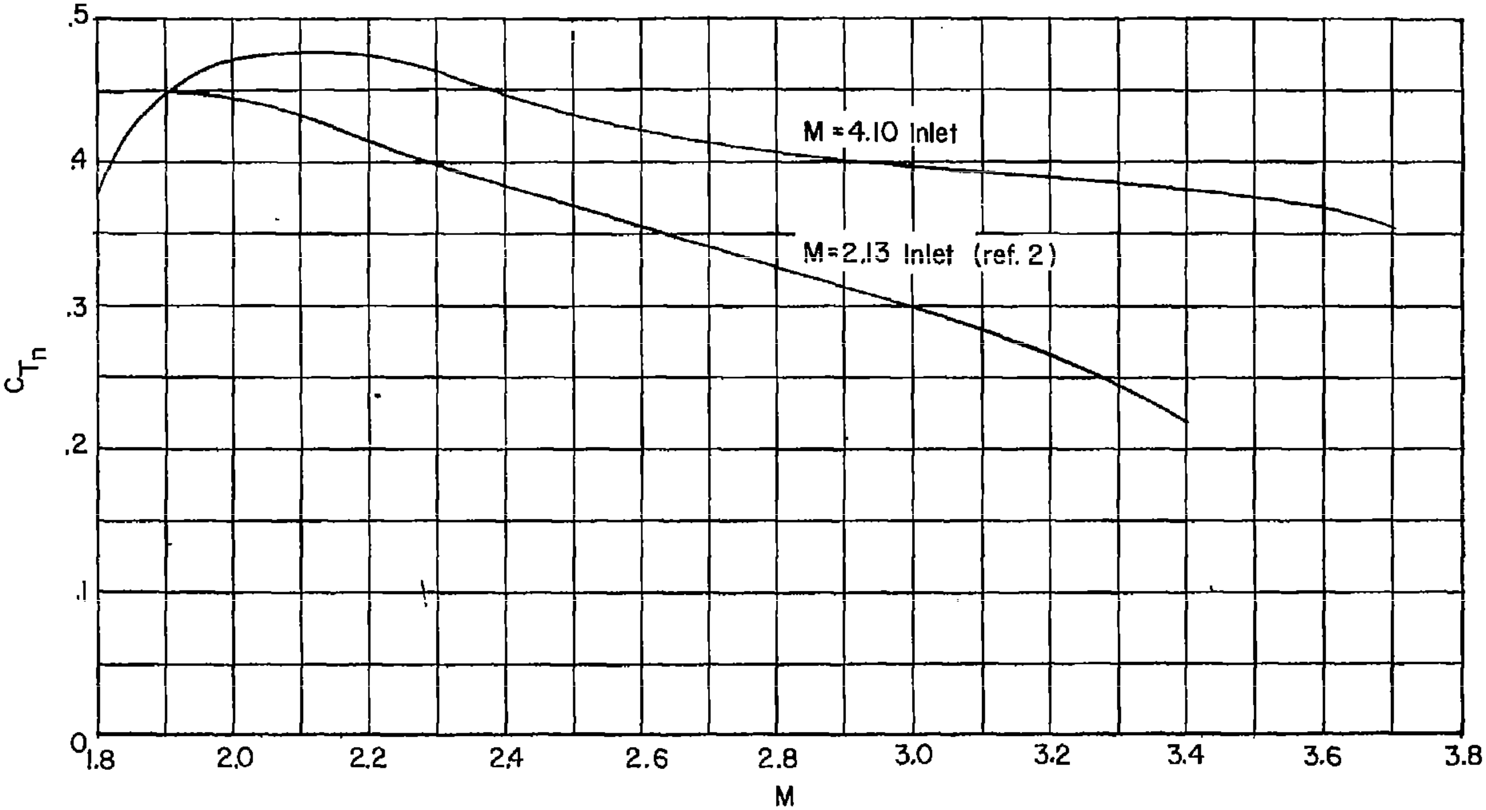

Figure 11.- Comparison of net thrust coefficient of present model and that of reference 2.

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